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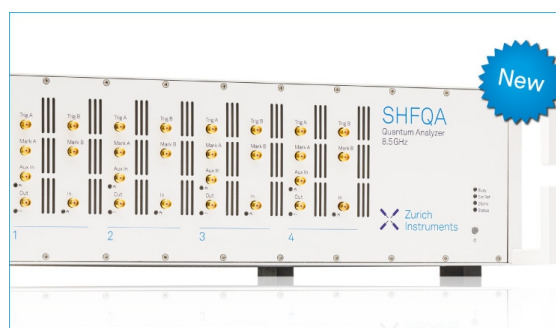
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# Computer-Aided Analysis of Cutting Processes for Brittle Materials

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**Abstract.** This paper is focused on 3D computer simulation of cutting processes for brittle materials and silicon wafers. Computer-aided analysis of wafer scribing and dicing is carried out with the use of the ANSYS CAE (computer-aided engineering) software, and a parametric model of the processes is created by means of the internal ANSYS APDL programming language. Different types of tool tip geometry are analyzed to obtain internal stresses, such as a four-sided pyramid with an included angle of 120° and a tool inclination angle to the normal axis of 15°. The quality of the workpieces after cutting is studied by optical microscopy to verify the FE (finite-element) model. The disruption of the material structure during scribing occurs near the scratch and propagates into the wafer or over its surface at a short range. The deformation area along the scratch looks like a ragged band, but the stress width is rather low. The theory of cutting brittle semiconductor and optical materials is developed on the basis of the advanced theory of metal turning. The fall of stress intensity along the normal on the way from the tip point to the scribe line can be predicted using the developed theory and with the verified FE model. The crystal quality and dimensions of defects are determined by the mechanics of scratching, which depends on the shape of the diamond tip, the scratching direction, the velocity of the cutting tool and applied force loads. The disunity is a rate-sensitive process, and it depends on the cutting thickness. The application of numerical techniques, such as FE analysis, to cutting problems enhances understanding and promotes the further development of existing machining technologies.

## INTRODUCTION

Ultra-precision machining is capable of manufacturing high quality surfaces with nanoscale roughness. Precision machining of brittle materials is gaining interest due to useful implementation in high-tech applications, such as semiconductor processing, micromechanical parts and high-end optical components [1]. Miniaturization of component manufacture and recent capabilities of high precision engineering allows enhancing the quality of ultimate devices. Moreover, progress in new optical and semiconductor materials (single crystals, composites, ceramics and glasses) with a structured surface or thin coating demands the evaluation of special technologies of careful treatment. The main factors affecting the surface quality are machine tool, cutting conditions and tool geometry, environmental conditions, material properties, chip formation, tool wear, vibration and thermal deformation [2]. In order to develop advanced technologies, it is necessary first to assess the nature of alterations produced in the surface layers of sheets or wafers by cutting tools [3].

Precision cutting by a diamond tool is an important technology, and it is generally used to separate a single crystal, a brittle wafer or a multi-crystalline sheet into several parts of desired size and geometry. Another application of these technologies is to produce mirror-image finish on brittle components used in optical devices. Machining in the ductile mode is introduced as an alternative method to achieve a high-quality finish directly on brittle materials without applying any post-processing. In the ductile mode, material is removed predominantly by chip formation in a way to finish the crack-free machined surface.

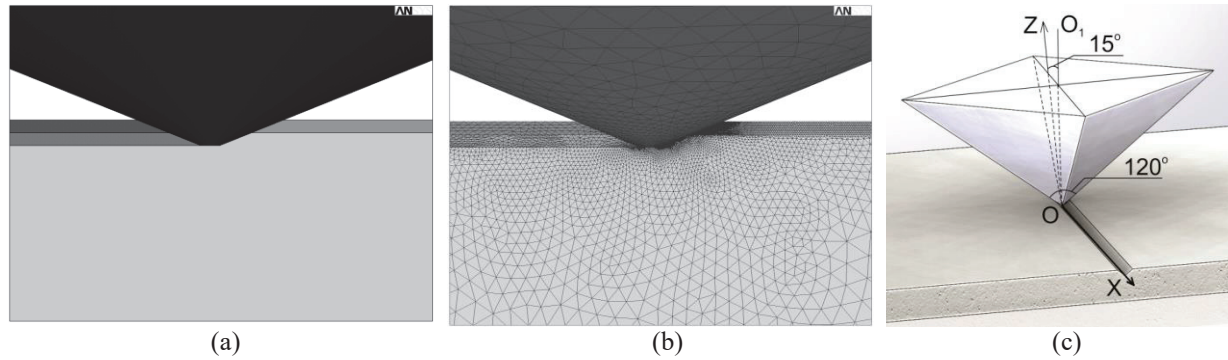
The inherent complexity of cutting processes is affected by a large number of influential factors, and this makes it extremely difficult to understand the mechanics of these processes by full scale testing. In machining, a detailed theory of cutting was developed for plastically deformable metals. For optical and semiconductor materials there is

no complete theory considering all the features of anisotropy, high hardness and brittleness, describing damage without plastic deformation and defect nucleation [4]. Rapidly upcoming FE software allows us to carry out computational experiments creating and investigating mesh models [5]. Finite element analysis was used to simulate both the structures and technologies of crystal devices. Investigation and virtual loading of mesh models assisted us in the search for optimal geometry of the cutting tool and the process parameters for any material. However, the current FE models of cutting processes and crack propagation in brittle materials fail to meet all the requirements of a comprehensive description. 2D formulation, static loading and other constraints of the models, which are used, confine the area of simulation effects.

This work is focused on modelling and 3D computer simulation of cutting processes for brittle materials, including samples with auxiliary coating or a specially treated surface.

## SIMULATION AND EXPERIMENTAL DETAILS

Generally, in diamond machining the surface quality of a brittle material is influenced by cutting speed, depth of cut and tool nose radius. The depth of cut has a quasi-linear proportion with cutting force, which results in heat and elastic-plastic deformation. Under the ductile mode, in the machining of brittle materials, such as silicon, germanium and glass, the depth of cut should be below a critical level to avoid crack propagation. Silicon is a material under study in this paper. This material is widely used for infrared optics and electronic applications. The 3D simulation of cutting a silicon wafer is performed with the application of the finite element method. APDL (ANSYS Parametric Design Language) programming is used to solve this simulation task. Initial parametric geometry is constructed by means of the ANSYS preprocessor (Fig. 1).



**FIGURE 1.** Cross section of the geometric model (a), FE mesh around the tool tip (b) and a 3D model of four-sided 120° pyramid with an inclination to normal axis of 15° (c)

The geometry consists of a silicon plate, which is glued to a flexible film, and a diamond tool. The constraints also include a z-fixed support along lower surface of the film. The cutting force is applied along the z-axis to the upper surface, so that the z-axis coincides with the gravity direction and the normal force loading on the tool. The x-axis coincides with a scratch line. A special top layer of the plate is intended for the analysis of the coating behavior and enables different values of contact cohesion. Scratches are produced on the surface of a silicon wafer by a diamond tip. The pyramid tip geometry corresponds to the Berkovich indenter, and it is sharpened as a four-sided pyramid with a large included angle (Fig. 1c). The loading force ranged from 0.1 to 1 N. The distribution of stress intensity in the wafer was analyzed for the pyramid with a comparable angle of about 120°. The surfaces of the workpieces were analyzed to verify the model by optical microscopy. The material was removed along the scratch by two symmetrical faces of the tool, which have the same cutting edge. The secondary cutting edges, belonging to two adjacent faces of the tool, formed scratch borders.

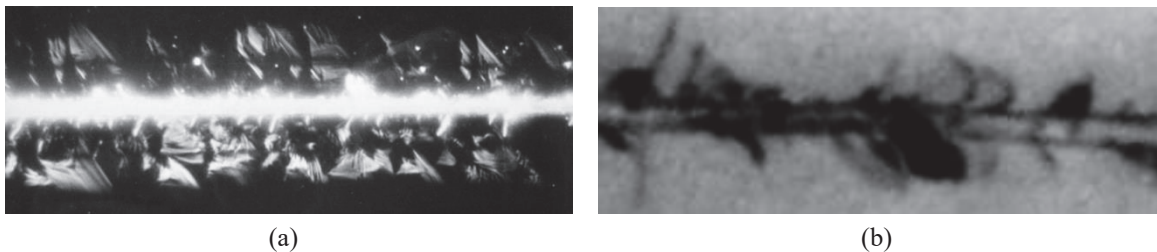
## RESULTS AND DISCUSSION

Normally, polished silicon wafers are subjected to scribing. Their surfaces are ready for any application and satisfy the optical or functional requirements before scribing. The scribing process should solve the following two basic tasks: to create a minimal defect zone near the scratch and to ensure safe separation of the crystal along the

scribe line. Chips and internal cracks are undesirable defects. The scratch on the surface of a silicon wafer was produced by a pyramid diamond tool. The response of the brittle material to force loading can be observed to proceed in three regimes; namely, elastic-plastic deformation, cracking and chipping.

*Optical microscopy.* Silicon crystal is a transparent material for infrared light, and it can be studied in situ using an optical microscope with a special add-on device. Analysis of scratches in infrared light is an operative control method in comparison with the X-ray and electron microscopy techniques; therefore, it can be used as a method for rapid quality control of machined silicon units.

The visible width of the scratch on the surface of a silicon workpiece after scribing is about 10  $\mu\text{m}$  under a force load of 0.1 N. The disruption of the material structure during scribing occurs near the scratch and propagates into the wafer or over its surface at a short range. In silicon, the progression of damage is complicated by the formation of an amorphous transformed layer underneath the tool tip. Examination of the scratch in the dark field has revealed that microcracks can be observed at any inclined position between  $3^\circ$  and  $15^\circ$  in herringbone order on the scratch borders (Fig. 2a). The deformation area along the scratch looks like a ragged band, but the stress width here is rather low (Fig. 2b). The scratch is followed by small lateral cracks. These lateral cracks link up to form chips, which eject away from the scratch. The surface chips implement destroying stress and generate a low stress state in the crystal integrally. However, here, some defects are situated under the surface, as it was obtained with the aid of infrared lighting. Asymmetrical front-reverse motion processing can bring reasonable quality without demolition of the crystal structure.



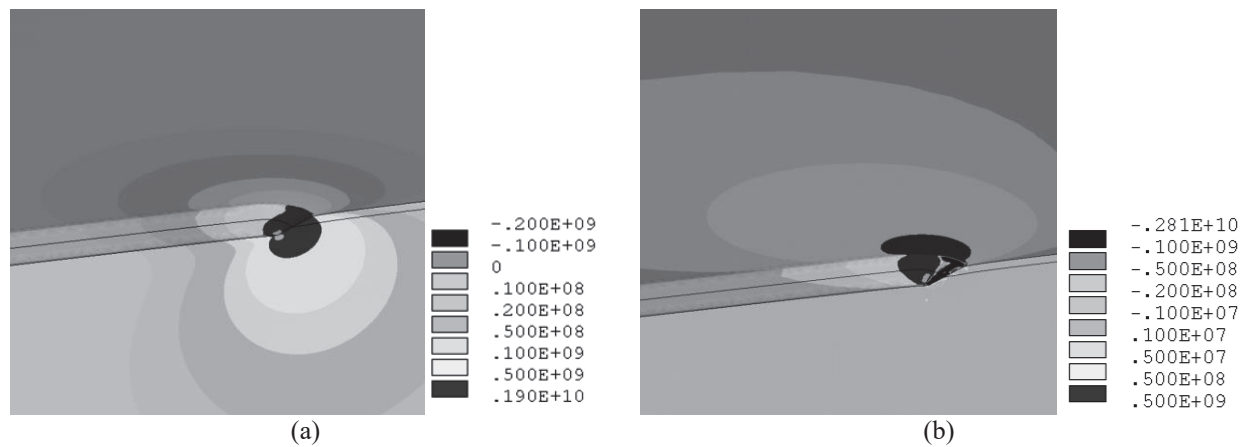
**FIGURE 2.** A scratch after scribing a single Si crystal in the  $[-1-1\ 2]$  crystallographic direction with a  $120^\circ$  four-sided pyramid: optical micrograph in dark field (a) and in indirect light (b); the length of the scratch shown is 0.05 mm

*Computer simulation.* The scribing of a silicon wafer can be represented in the computer simulation as a special case of cutting. We can simulate the shaping of a scratch on the surface under the diamond edge by analogy with threading of metal by a lathe tool. Just some differences of cutting for silicon should be added in the model. For metal cutting, we set the depth and width of cut, the cutting speed and feed, but the cutting forces are derived from the cutting mode, tool geometry and material properties. The depth of cut is significantly dependent on the cutting edge radius. The cutting mechanism for metal is chip formation due to metal shearing. Silicon is a brittle and hard material. For scribing the brittle material, we should set just the normal force on the tool. Then the depth of the cut, the scratch width and the tangential component of the cutting force can be derived from the predetermined normal force and also from the tool tip geometry and the material properties. Based on the advanced theory of metal cutting, it is possible to state a similar theory for the cutting of brittle semiconductors and optical materials.

In cutting a silicon wafer, the diamond tool produces hydrostatic pressure on the workpiece. Scribing induces singular deformation of the wafer at the tool edge. A compression zone occurs just under the diamond tip. The calculated stress field in the plate, which although is dominated by the shear and compression components, nevertheless contains an area of tension on the surface, which creates conditions for cracking. The scratch quality is heavily dependent on the angle of inclination and the tool geometry. Cutting is still possible with inclination less than  $15^\circ$ , which leads to minimum chipping on the scratch borders. The fall of stress intensity along the line perpendicular to the scratch from the tip point and the distribution of tangential stresses were calculated (Fig. 3). The stress values and the stress distribution essence do not depend greatly on the tip shape.

The internal stresses are most affected by the tip radius. The parameter of stress intensity represents the maximum shear stresses, and it was also calculated. Ductile chip formation is a result of large compressive and shear stresses in the chip formation zone. Large compressive stresses can be generated due to a small chip thickness, which is smaller than the radius of the cutting tool edge. Following the diamond tip motion, the defects may arise around the scribe line due to a complicated mode of deformation, which is not a plane one. The crystal quality and defect dimensions were determined by the mechanism of scratching, which depends on the diamond tip shape, the

scratching direction, the velocity of the cutting tool and applied loads. The disunity is a rate-sensitive process, and it depends on the cutting thickness. The calculated values of stress intensity and tangential stresses correspond to the theoretical values for silicon up to 4% in the  $[-1-1\ 2]$  crystallographic direction.



**FIGURE 3.** Distribution of stress intensity in the middle of contact zone (a) and tangential stresses in cross-section (b)

The numerical FE model developed in this study allows any coatings and layers near the workpiece surface to be analyzed. This approach has advantages over the experimental methods of investigation, since it gives direct quantitative evaluation of adhesion from scratch data, such as critical loads, on the basis of different criteria. The deformation can be observed to progress in four stages, namely, elastic surface deflection, plastic deformation of the coating, ring crack formation, and finally compressive cleavage of the coating ahead of the tool tip.

## CONCLUSION

A numerical model for the computation of brittle material scribing has been developed and used to study the diamond machining process. Silicon wafer scribing has been represented in the computer simulation as a special case of cutting. The parametric geometry of a silicon workpiece and a diamond tool has been created in the ANSYS pre-processor. Suitable force loading and constraining degrees of freedom have been applied to a 3D mesh model. The distribution of stress intensity and tangential stresses has been calculated. The internal stresses are mostly affected by the tip radius.

Full-scale experiments corresponding to the computation model were carried out. Scratches were produced on the surface of a silicon wafer by a diamond tip sharpened as a four-sided pyramid with a large included angle of  $120^\circ$ . The loading force was set in a range from 0.1 to 1 N. The scratches were studied using an optical microscope with special add-on devices for infrared and dark-field techniques.

The calculated values of stress intensity and tangential stresses correspond to the theoretical values for silicon. The application of numerical techniques, such as FE analysis, to solve cutting issues enhances understanding and promotes the further development of existing machining technologies.

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